60007 - 60001

DRAFT

Deep Drill Core

224 cm

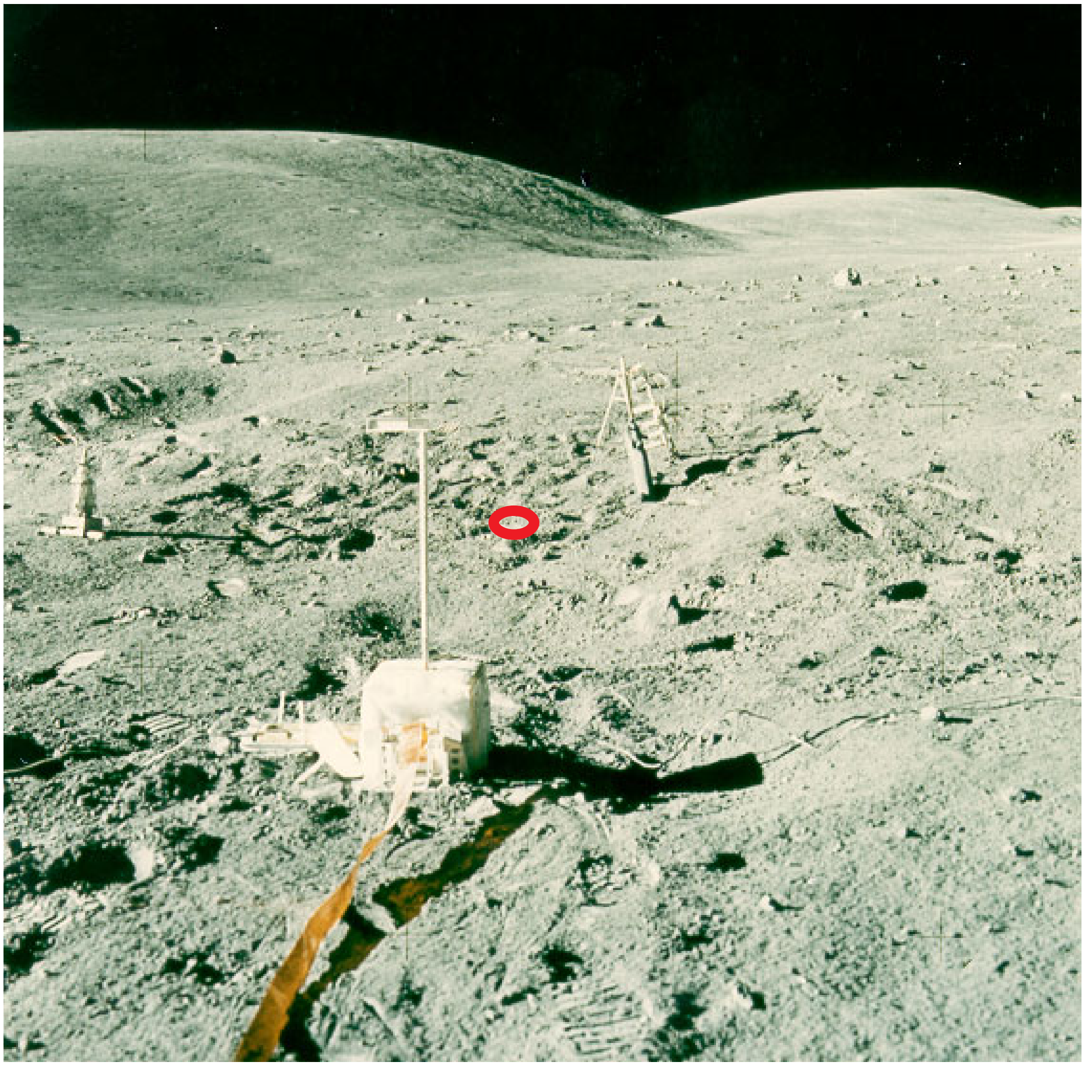


Figure 1: Photo of ALSEP site at Apollo 16 after deep drill core was taken. The drill moter is in view. Approximate location of drill hole in red. Stone Mountain about 5 km distant. AS16-113-18367.

Introduction

Three cores were taken about 50 m apart at the ALSEP station near the LM – the deep drill string 60007 – 60001, and two double drive tubes 60010/60009 and 60014/60013 (Sutton in Ulrich et al. 1981). However, "few, if any, modal variations are stratigraphically correlatable" between these three, nearly adjacent, cores (Simon et al. 1978). The soil in this area was loosely compacted and the cores were easy to obtain, probably because of numerous small craters in the vicinity. It had been hoped that material (distinct layers) from both North Ray and South Ray craters could be identified in these cores. However, gardening of the regolith seems to have obliterated distinct layering (Arnold 1975) and no correlation of layering could be found between the three nearly adjacent cores.

The deep drill string was separated into two sections of three stems each on the lunar surface (60007, 60006 and 60005) and (60004, 60003, 60002 and 60001bit).

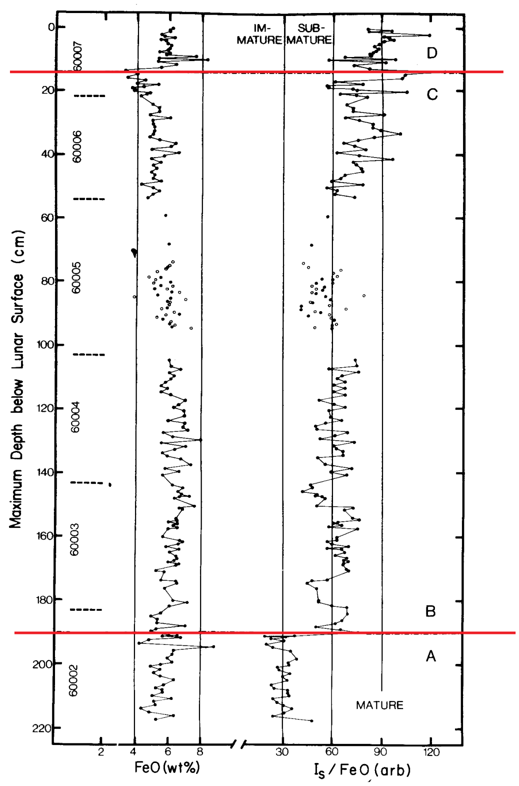


Figure 2: Maturity index (Is/FeO) of 60007 - 60001 deep drill core (from Gose and Morris 1977). Core segment 60005 was too disturbed to establish position of samples.

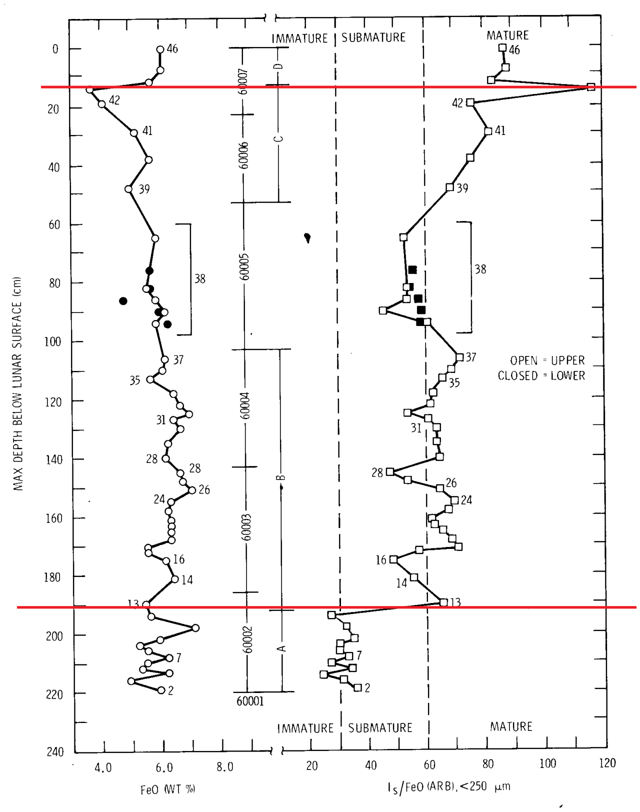


Figure 3: Average stratigraphic variations of maturity index of 60007 - 60001 deep drill core, based on divisions defined by Duke and Nagle (1994)(from Gose and Morris 1977).

Apparently a substantial amount soil material fell out of the upper section, because much of 60005 and some of 60006 was found to be partially void on return to Houston. The top section (60007) was only half full (Horz et al. 1972 and Duke and Nagle 1976 offer various explanations for this).

Excerpt(s) from Horz et al. (1972), page 7-52: *"The deep drill stem (60001 to 60007) was taken approximately 175 m southwest of the LM and 25 m south of the ALSEP site in a generally flat spot in an area of rolling topography with numerous 2- to 6-m craters and relatively loose, uncompacted soil. Two other core samples and soil from seven penetrometer stations were taken within 100 m of the drill stem, which enables the most detailed correlation and reconstruction of lunar soil strata to date*". - - - - - Based on X-radiographs: *"The surficial 15.7 cm of the drill stem is relatively fine grained, contains an abundance of glass, and has been subdivided into four subunits. Of these, the uppermost 2 cm is relatively dark and crumbly and is underlain by a 3.5 cm zone that is high in whitish aggregates. Indistinct massive bedding characterizes the next 10 cm, with a rock concentration at 10.5 cm marking a break in bedding. The massive zone tends to be poorly sorted and contains a coarse fraction dominated by glass fragments, droplets and feldspar fragments. The lowest 6.4 cm of section 60007 is reverse graded and coarse grained and contains a diversity of rock fragment types. The X-radiographs indicate that the coarse material at the base of section 60007 continues into section 60006 into the regolith for a total of approximately 50 cm. Bedding is thicker and more massive toward the top of this coarse-grained interval, but there are more large semiopaque rock fragments in the thinner beds at he base of the zone"*. - - - - (part of 60006 and all of 60005 were partially void) - - - - *"The basal sections of the drill stem are fine grained in comparison to the upper sections. The top 11 cm of 60004 is very fine grained, followed by 25 cm of lumpy coarse material with a few distinct rock fragments. The basal 85 cm of the drill string is fine grained with a rock layer only in the middle of section 60003 at a depth of about 135 cm below the lunar surface."*

Meyer and McCallister (1977) and Papike et al. (1982) review all of the data for the Apollo 16 deep drill and discuss the various stratigraphic layers and whether the boundaries between layers are "*ancient lunar surfaces*" or not. The discontinuity between layers A

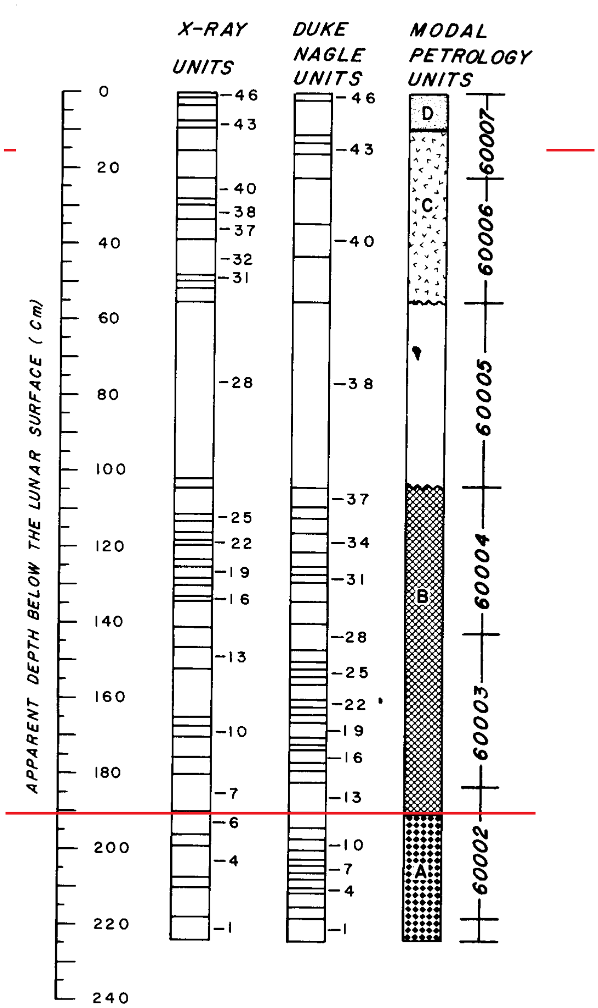


Figure 4: Comparison of three different schemes defining the apparent layering in deep drill 60007 - 60001 (from Vaniman et al. 1976).

and B at 190 cm may be a time horizon based on track studies and He and Ar isotopes, and the C/D contact at 13 cm may also be a fossil surface (discussed below). There does not appear to be complete agreement between workers from various disciplines, but it does appear that there are distinct variations along the deep drill. It is also apparent that accumulation of locally derived highlands material took place over about a billion years.

Petrography

Gose and Morris (1977) determined the maturity along the deep drill (figures 2 and 3) and discussed the depositional history. They seem to have verified the "contacts" (A/B, C/D) distinguished by Vaniman et al. (1976) based on detailed petrographic analysis of thin sections. Unit A (from 190 to 225 cm) is immature and is distinguished by an abundance of large lithic clasts and abundant yellow glass. Unit B contains fewer large lithic clasts, but has a larger proportion of green glass. Unit C contains abundant large plagioclase fragments and lack orange glass. Unit D has fewer mafic mineral fragments and fewer glasses than the rest of the core.

Vaniman et al. (1976) provide an abundance of modal mineralogy for the whole drill string and distinguish four separate units (see table). In thin sections #60002,386 they found 3.7% agglutinate, #60003,242 = 10.2% agglutinate, #60007,246 = 4.1% agglutinate, but in general they did not find many agglutinates considering the mature-submature nature of the core as indicated by Is/FeO. However, Heiken et al. (1973) found 30-50% agglutinates in the top of the core (90-

Average modal content of major units A16 drill.

	From thin section study by Vaniman et al. 1976				*from Heiken 1974*
unit	**A**	**B**	**C**	**D**	**60007**
depth	190-225 cm	~100-190 cm	6-~60 cm	0-6 cm	top
Agglutinates	0.4	0.9	1.6	1.2	42.7
Basalt, feldpathic	0.7	0.4	0.3	0.8	-
Breccia, dark matrix	5.1	3.7	2	4.4	12.3
Breccia, light matrix	9.6	2.8	3.6	2.4	20
Anorthosite	3.9	0.3	0.4	0.3	1.9
Norite + Troctolite	3.1	2.7	3.8	2.2	0.3
RNB + poik	3.8	1.2	3.4	2.7	
Plagioclase	10.5	7.6	13.7	9	13.7
Olivine + Pyroxene	1.8	1.5	1.3	0.4	0.6
Opaque (Ilmenite)	0.4	0.2	0.3	0.2	
Glass (all)	3.3	2.8	2.3	1.6	7.8

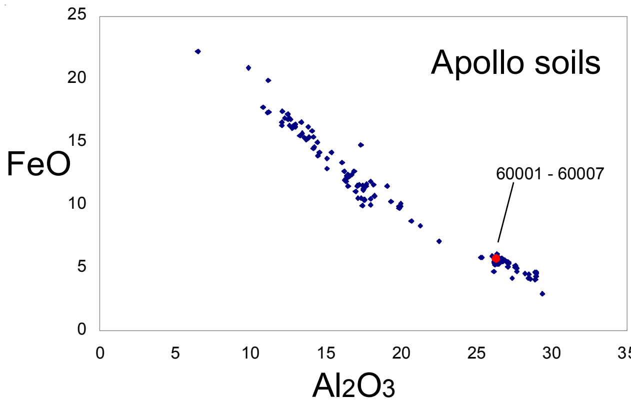


Figure 5: Chemical composition of Apollo 16 deep drill compared with other lunar soils.

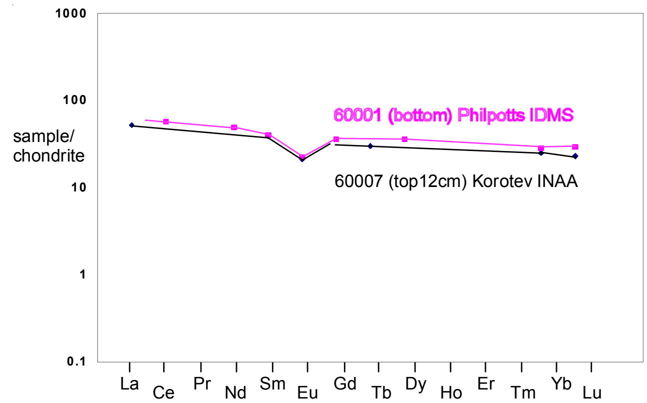


Figure 6: Normalized rare-earth-element composition for top and bottom of Apollo 16 deep drill (see table).

150 micron splits) and there is a significant lack of agreement between agglutinate counts from bulk sample and thin section petrography. Meyer and McCallister (1977) also conclude that there are four major units.

Out of more than 300 glass particles in the deep drill, Naney et al. (1976) found 4-5 small green glass particles with high-alumina, silica-poor content (HASP). They were found distributed throughout the drill core, and it is thought that they formed by some sort of volatilization, condensation process.

Delano (1975) carefully studied mare basalt fragments from 60003 and was able to relate them to their apparent source – Mare Nectaris, 100 km to the south.

Carter (1975) and Haggerty (1978) reported on an unusual *Rusty Particle* found in 60002. This iron particle was encrusted with feathery growths of FeOOH. And it was found inside of a deep drill segment where it was well protected from terrestrial contamination.

Buried Surface ?

Duke and Nagle (1974), Bogard and Hirsch (1975), Vaniman et al. (1976), Blanford and Morrison (1976), and Heymann et al. (1978) studied an apparent buried surface at about 190 cm – in drill core section 60002. The unit (A) below this boundary is immature (figure 3) and has been found to have a distinctly different isotopic composition for rare gas (Bogard and Hirsch 1975) and nitrogen (Becker and Clayton 1977). Blanford and Wood (1978) reevaluated whether this contact was an ancient regolith or a simple depositional boundary. If it is an ancient surface, it has a model exposure age of 3-7 x 10^6 years and a reworking depth of 0.5 cm.

Chemistry

The chemical composition of the Apollo 16 deep drill is relatively homogeneous for its entire length (Korotev 1982, 1991), with no chemically distinct layers apparent. Nava et al. (1973 and 1976), Philpotts et al. (1973), Boynton et al. (1976) and Gold et al. (1977) and Ehmann et al. (1977) also analyzed various portions the deep drill core. This data is summarized in tables 1 and 2 and figures 5 and 6. The detailed chemical composition of the Apollo 16 deep drill is found in an appendix to the paper by Korotev (1991).

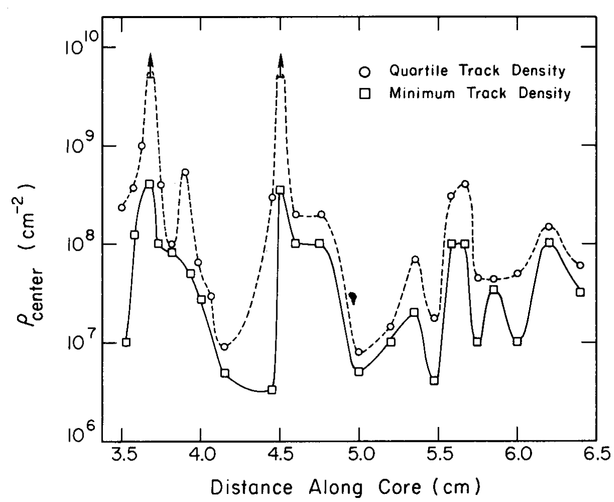


Figure 7: Cosmic ray track density in 60003 showing fine structure (from Price et al. 1975). Depth is from top of 60003 (not lunar surface).

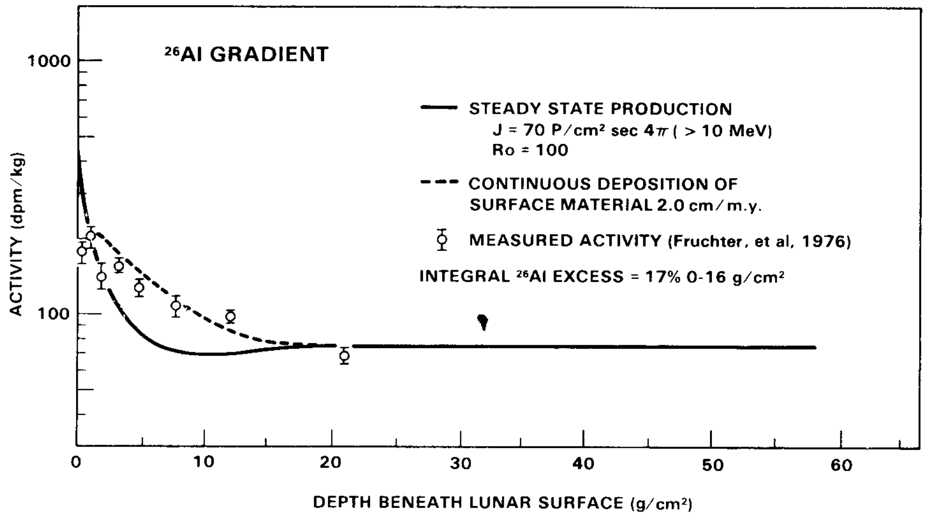


Figure 8: Profile of 26Al in top portion of Apollo 16 deep drill (from Evans et al. 1980).

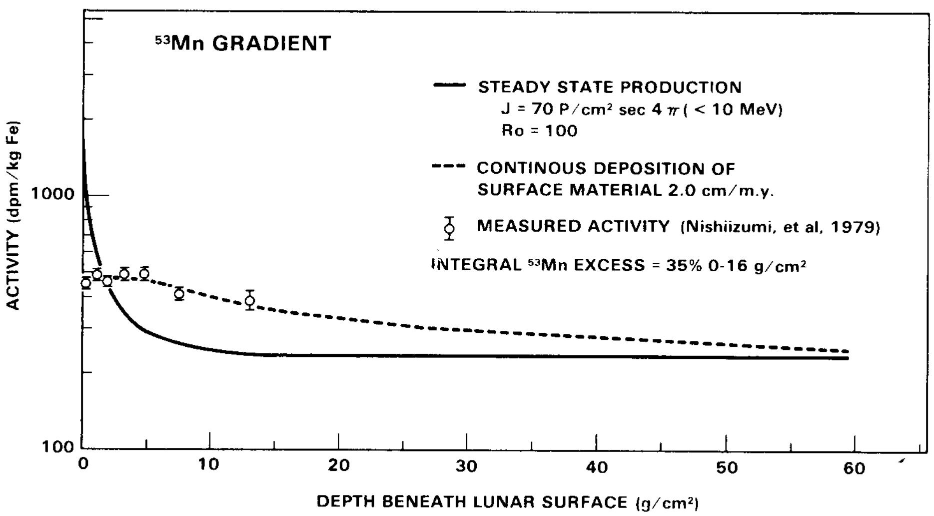


Figure 9: Profile of 53Mn in top portion of Apollo 16 deep drill (from Evans et al. 1980).

Cosmogenic isotopes and exposure ages

Nishiizumi et al. (1976), Fruchter et al. (1977) and Evans et al. (1980) determined the cosmic ray induced activity of ^{26}Al and ^{53}Mn in the Apollo 16 deep drill (figures 8 and 9). Fireman et al. (1973) reported data for the isotopic composition of Ar (figure 10).

Wieler et al. (1982) carefully studied the isotopic composition of noble gases in plagioclase separates and determined that the ratio of the Ne component from solar flares and the solar wind was distinctly different for the bottom of the Apollo 16 deep drill core.

Russ (1973) reported the neutron stratigraphy.

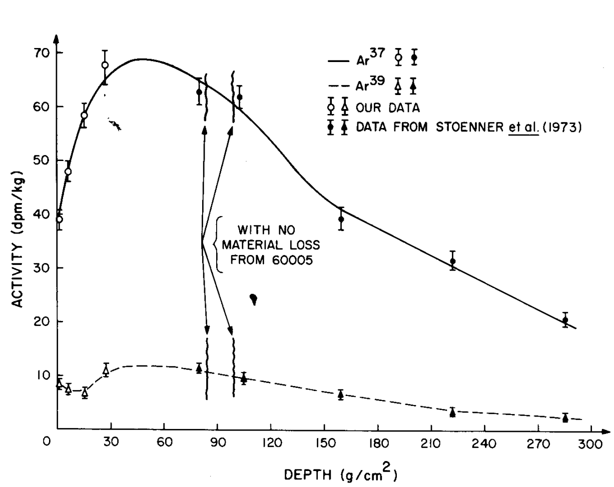


Figure 10: Isotopic composition of Ar as function of depth in Apollo 16 drill (Fireman et al. 1973).

Other Studies

The substantial amount of cosmogenic rare gas that is found throughout the Apollo 16 drill core indicates that fresh ejecta from North Ray and South Ray craters is not a significant component of the core (Bogard and Hirsch 1975). Values of $^{4}He/^{20}Ne$, $^{20}Ne/^{36}Ar$ and $^{40}Ar/^{36}Ar$ from the lowest 35 cm of the core (unit A) are distinct from all other portions of the core and from all Apollo 16 soils except 61220. Heymann et al. (1978) also report noble gas measurements for the deep drill.

Becker and Clayton (1977) found that the nitrogen isotope ratio in the coarse-grained unit at the bottom of the Apollo 16 drill (unit A?) was very light (figure 11) and concluded that the flux and the isotopic ratio of solar wind nitrogen has changed significantly over time (see Clayton and Thiemens 1980).

Behrmann et al. (1973), Price et al. (1975) (figure 7), Goswami et al. (1976), Fleischer et al. (1974), Blanford and Morrison (1976), Blanford and Wood (1978), Crozaz and Dust (1977), Crozaz (1978) and Wieler et al. (1982) all studied cosmic ray tracks in various portions of the Apollo 16 deep drill. Indeed, considerable effort has been expended trying to understand what the track data tell us, and various authors identify various layers in the core based on track data.

Crozaz (1978) explained: *"there is a basic difference in philosophy on the part of people who advocate slow accumulation (mainly researchers working with tracks) and emplacement of big slabs (essentially Morris and Gose). Slow accretion (mm to cm layers) should be common compared to occasional large depositions just because the frequency of impacts decreases steeply as the size of the impacting body (and its ejecta blanket) increases. This is precisely what trackologists deduce from their studies: they have seen repeated evidence for the deposition of small layers (mm to cm) and occasional evidence for the deposition of a much larger layer (for example the coarse-grained layer in the Apollo 17 drill stem). It is not clear to this author that the ferromagnetic resonance data cannot be interpreted in the same way. The data also show variations on a mm to cm scale which could reflect the slight maturity variations of successive thin layers of local origin."*

Banerjee et al. (1977) reported the natural remanant magnetization (NRM) of the bottom of the drill core (60004-60002) and *tentatively* ascribe variation in the stable NRM to fluctuations in the magnetic field of the moon over time! *(however, this is considered unlikely)*

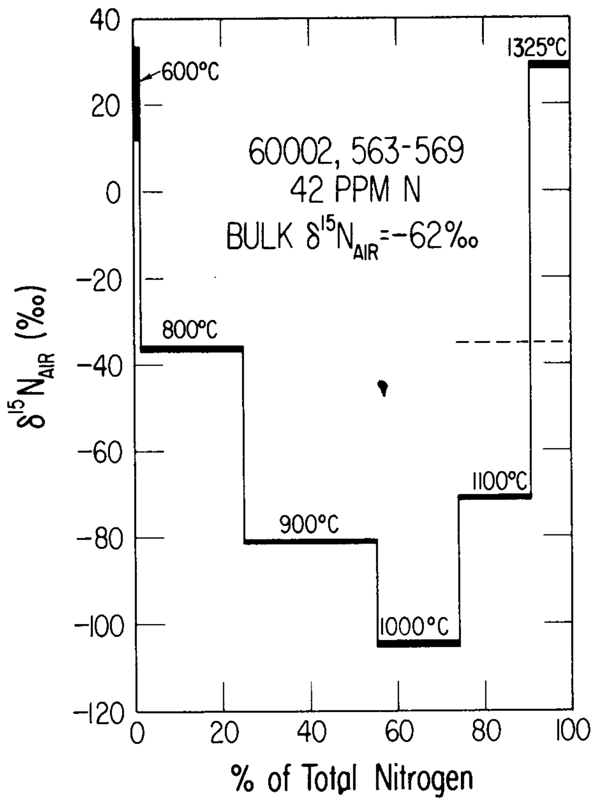


Figure 11: Isotopic composition of nitrogen in sample from near bottom of Apollo 16 deep drill (Becker and Clayton 1977).

Processing

The collection of the Apollo 16 core is described in the Preliminary Science Report for Apollo 16 and by Horz et al. (1972). Carrier (1974) and Allton and Waltz (1980) have presented the depth calculations of the core (figure 12). Fryxell and Heiken (1974) and Nagle and Duke (1974) have discussed how the samples were dissected and prepared. After dissection was complete the core segments (except 60005) were impregnated and encapsulated in epoxy in order to make thin sections. A reference section was preserved for future reference – see photomozaic attached. (Note: the different segments were photographed at different magnifications). Segment 60004 may be upside down!

According to the core catalog (Duke and Nagle 1976) page 16-34, some sort of bad spill occurred for sample vials of 60007 – after dissection (I wish I had a picture!).

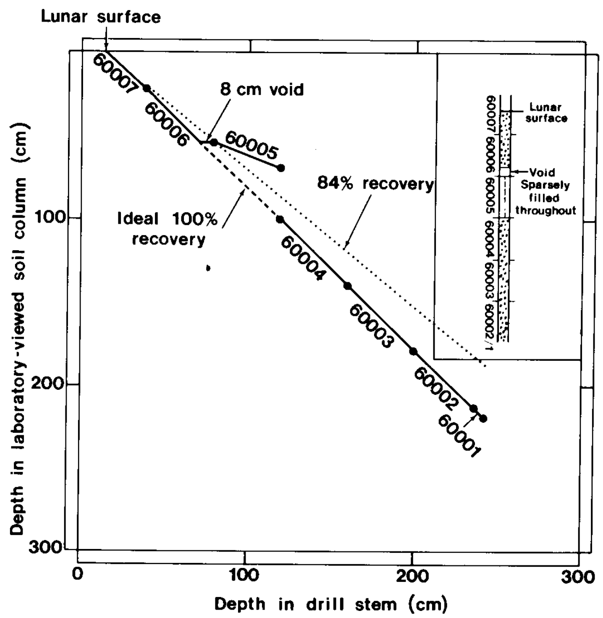


Figure 12: Depth of samples in Apollo 16 deep drill (Allton and Waltz 1980).

Table 1. Chemical composition of A16 deep drill.

reference	Gold77		Nava73			Philpotts73					Nava76	
weight	60002	60005	60007	60006	60001	60007	60006	60004	60003	60001	60002	
SiO2 %	44.3	43.6	45.2	45.4	45.3						44.8	(a)
TiO2	0.72	1.04	0.39	0.52	0.56						0.56	(c)
Al2O3	26.3	27	29.8	27.5	26.2						25.04	(a)
FeO	6.59	6.61	3.6	4.9	5.3						6.66	(a)
MnO	0.08	0.1	0.02	0.04	0.06						0.07	(a)
MgO	6.85	7.54	4.43	5.83	6.42						7.04	(a)
CaO	15.4	16.24	16.35	15.42	15.38						14.27	(a)
Na2O	0.47	0.45	0.42	0.43	0.49						0.48	(a)
K2O	0.17	0.17				0.085	0.094	0.13	0.13	0.14	0.13	(b)
P2O5			0.08	0.09	0.13						0.12	(c)
S %												
sum												
depth						22 cm	57 cm	103 cm	182 cm	223 cm		
Sc ppm	10.8	12.4										
V	28.4	27.9										
Cr	864	913									753	(a)
Co	49.7	30.4										
Ni	773	397										
Cu												
Zn												
Ga												
Ge ppb												
As												
Se												
Rb						1.97	2.29	3.24	3.1	3.46		(b)
Sr						168	166	170	168	173		(b)
Y												
Zr						135				202		(b)
Nb												
Mo												
Ru												
Rh												
Pd ppb												
Ag ppb												
Cd ppb												
In ppb												
Sn ppb												
Sb ppb												
Te ppb												
Cs ppm												
Ba	169	139				108				159		(b)
La	14.3	12.5										
Ce	35.6	33.7				23.8				34.5		(b)
Pr												
Nd	20	16				15.5				22.2		(b)
Sm	6.62	6				4.33				5.94		(b)
Eu	1.14	1.25				1.15				1.25		(b)
Gd						5.28				7.04		(b)
Tb	1.04	0.89										
Dy	5.4	3.9				5.43				8.7		(b)
Ho												
Er						3.31				4.64		(b)
Tm												
Yb	4.7	4.2				3.11						(b)
Lu	0.76	0.67								0.72		(b)
Hf	5.17	4.62								4.78		(b)
Ta	0.67	0.65										(b)
W ppb												
Re ppb												
Os ppb												
Ir ppb												
Pt ppb												
Au ppb												
Th ppm	1.66	1.7										(b)
U ppm												

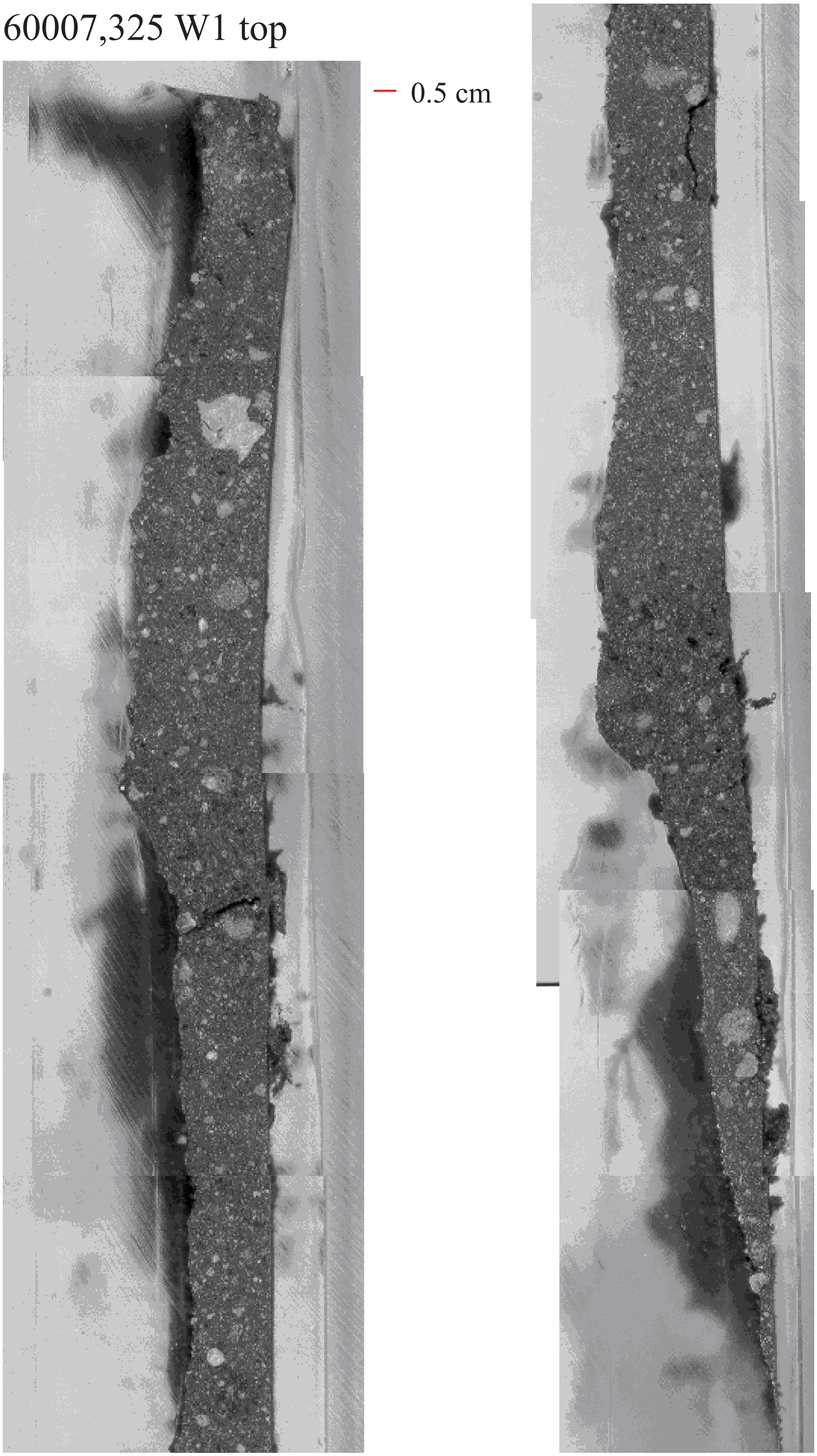
technique: (a) AA, (b) IDMS, (c) colorometric

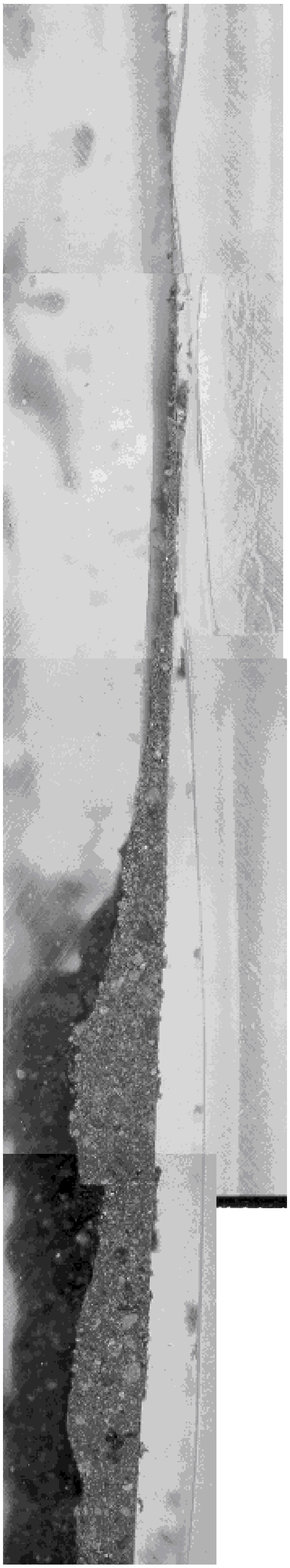
Table 2. Chemical composition of A16 deep drill.

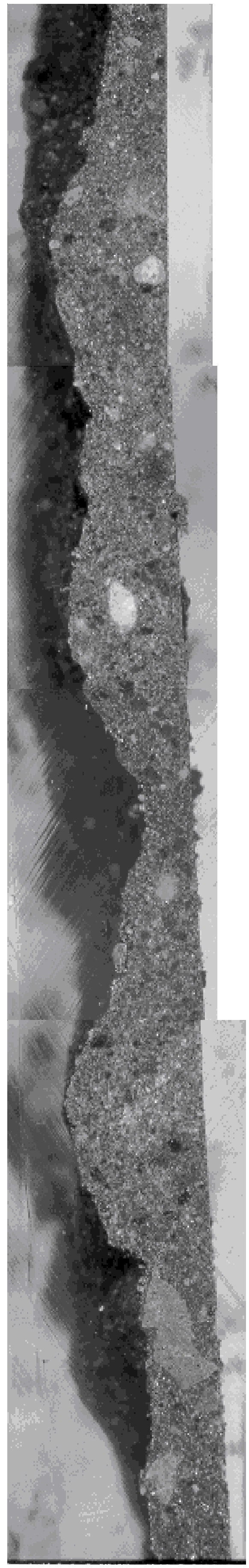
								60007		
reference	Korotev82					Boynton76		Korotev91		
weight	60002	60003	60004	60005	60002			ave	ave.	
depth	194 cm	180 cm	137	95				top11cm	entire	
TiO2					0.85	0.74	0.7		core	
Al2O3					25.5	26.8	26.8			
FeO	5.56	5.86	5.94	5.78	7.07	7.05	7.04	5.19	5.5	(a)
MnO					0.075	0.076	0.077			
MgO					7.46	8.29	6.47			
CaO	15.8	15.3	15.4	15.1	16.7	16.8	15.5	15.8	15.4	(a)
Na2O	0.507	0.485	0.477	0.477	0.473	0.47	0.487	0.438	0.465	(a)
K2O					0.126	0.123	0.123			
P2O5										
S %										
sum										
Sc ppm	9.34	10.23	11.22	10.63	11	10.3	10.3	9.09	9.71	(a)
V					37	16	20			
Cr	736	818	828	797	1000	990	950	750	790	(a)
Co	31.6	30	24.3	24.5	48.7	49.7	55.1	27	30.5	(a)
Ni	415	480	330	330	640	700	740	375	439	(a)
Cu	note: These are representative or averages of Randy Korotev's many analyses - see publications.									
Zn					24.7	26.7	25.7			(b)
Ga					5.1	5.5	6			(b)
Ge ppb					1060	1220	1250			(b)
As										
Se										
Rb										
Sr	190	170	170	170				166	177	(a)
Y										
Zr	210	245	240	225				160	205	(a)
Nb										
Mo										
Ru										
Rh										
Pd ppb										
Ag ppb										
Cd ppb					98	135	116			(b)
In ppb					12.5	16.6	15.4			(b)
Sn ppb										
Sb ppb										
Te ppb										
Cs ppm	0.16	0.18	0.17	0.12						(a)
Ba	145	164	155	158	200	170	160	137	144	(a)
La	12.5	13.2	13.7	13.4	14.4	14.7	15	12.4	13.2	(a)
Ce	34.3	36.8	37.7	36.2	38	38	39			
Pr										
Nd										
Sm	5.93	6.37	6.71	6.48	6.2	6.1	6.3	5.75	6.16	(a)
Eu	1.2	1.19	1.22	1.22	1.27	1.26	1.24	1.17	1.2	(a)
Gd										
Tb	1.27	1.34	1.45	1.38	1.4	1.5	1.4	1.1	1.22	(a)
Dy					8	7.9	7.8			
Ho										
Er										
Tm										
Yb	4.21	4.7	4.8	4.63	4.7	4.6	4.6	4.05	4.34	(a)
Lu	0.619	0.688	0.719	0.691	0.64	0.62	0.64	0.57	0.6	(a)
Hf	4.54	5.1	5.17	5.07	4	4	4	4.45	4.71	(a)
Ta	0.66	0.72	0.75	0.74	0.7	0.5	0.5	0.505	0.54	(a)
W ppb										
Re ppb										
Os ppb										
Ir ppb	12.7	13.7	10.9	9.7	18.3	19.4	20.6	12.8	14.4	(a)
Pt ppb								7.8	9	(a)
Au ppb					9.2	10.6	11.5			(b)
Th ppm	2.25	2.8	2.7	2.45	2.2	2.3	2.4	2.07	2.23	(a)
U ppm	0.55	0.65	0.6	0.59	0.8	0.8	0.8	0.5	0.57	(a)

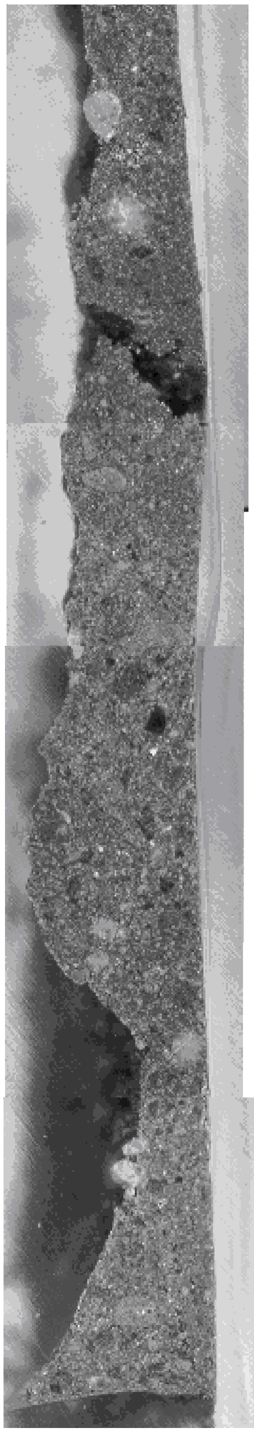
technique: (a) INAA, (b) RNAA

60007,325 W1 top





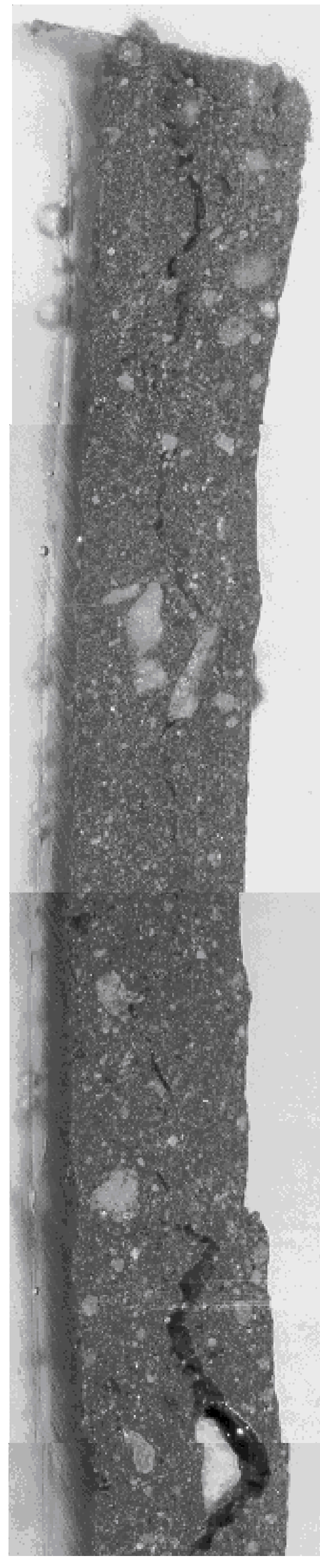




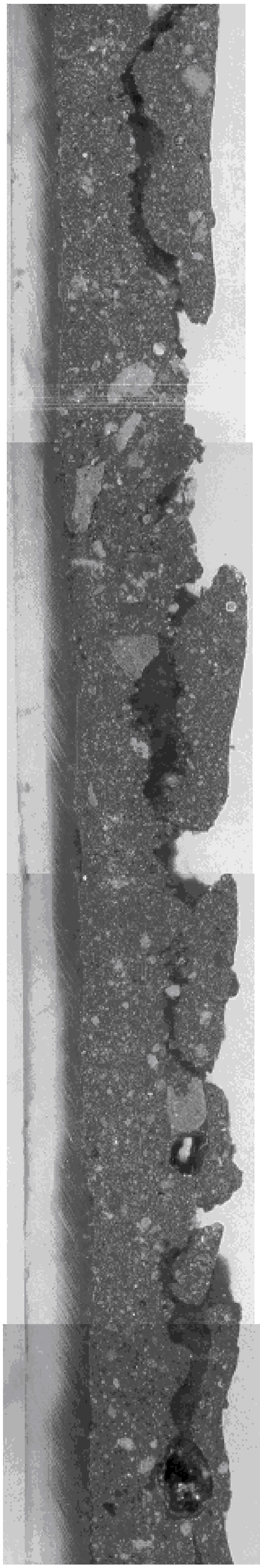
about 22.4 cm

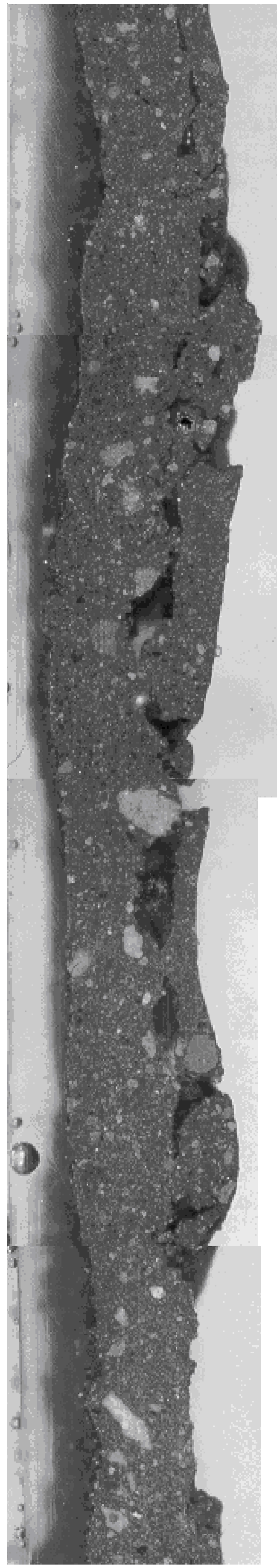
60007,325 bottom

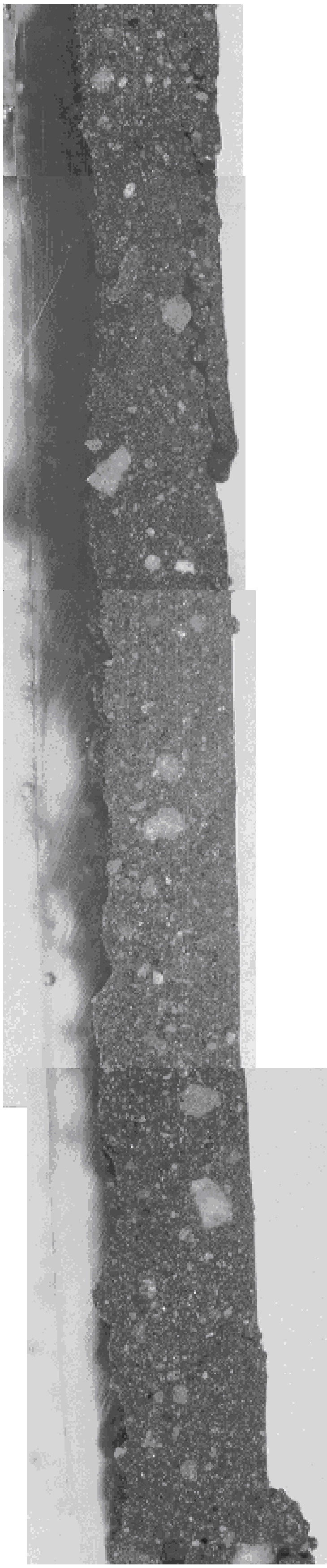
top of 60006,212 W1

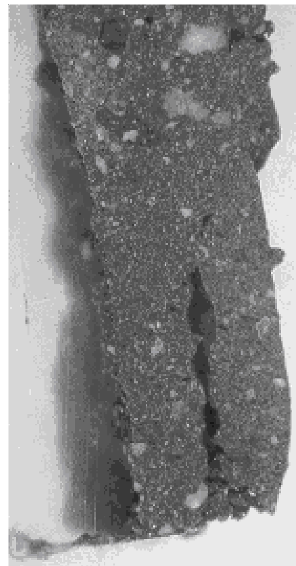


about 23 cm









about 54.4 cm

bottom of 60006,212

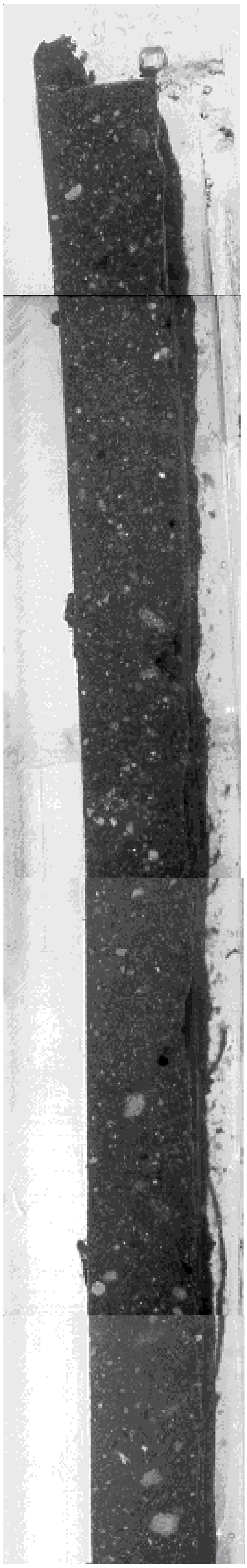
Note: The bottom of 60006 was missing.

60005 ?

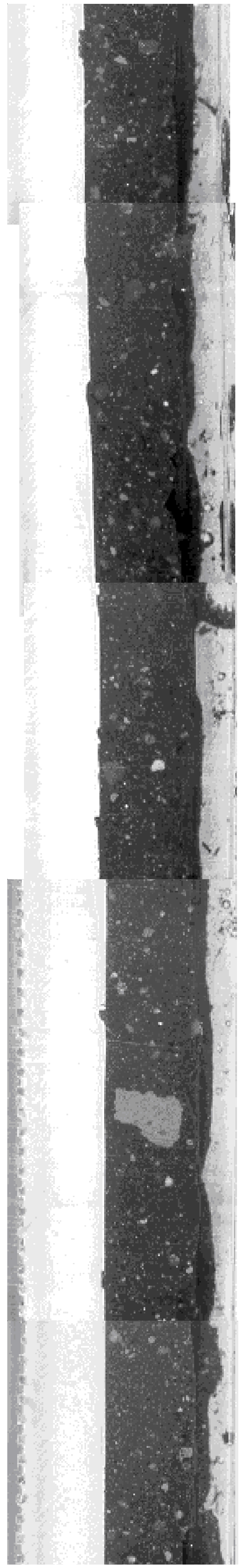
Note: 60005 was found to be about half empty, and had possibly been well mixed, probably because about half of the dirt fell out on the moon. It was not "dissected" in the usual manner.

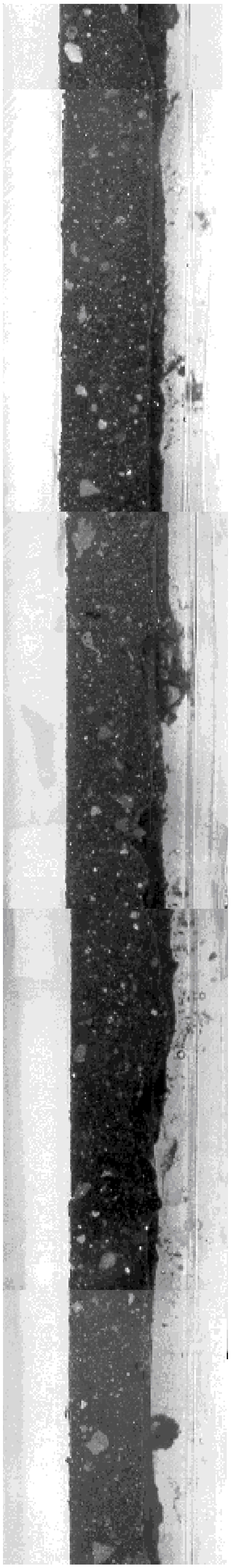
60004,418

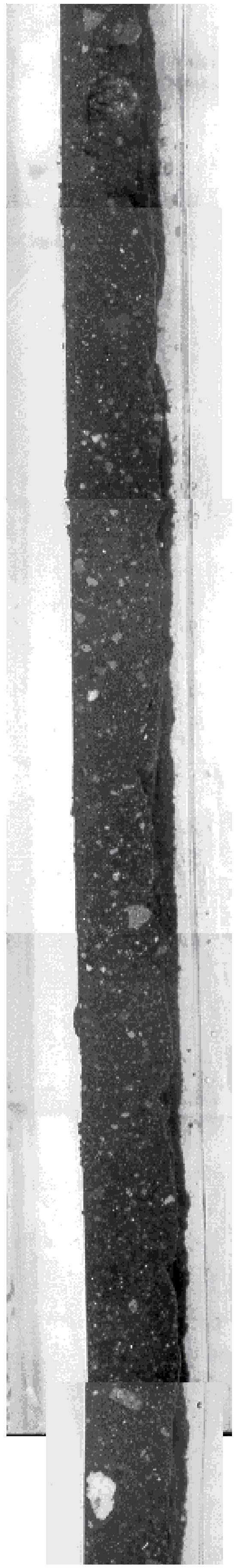
top, I think ?



about 103 cm







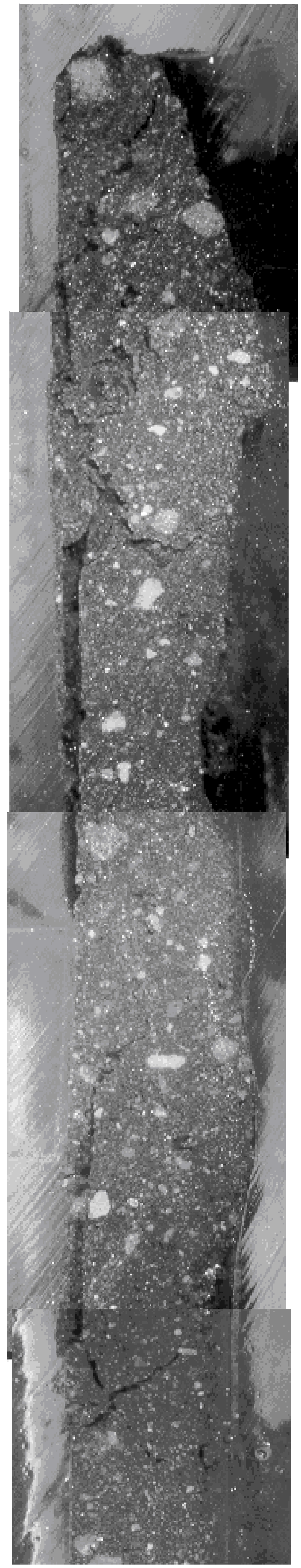
about 140.5 cm

60004,418

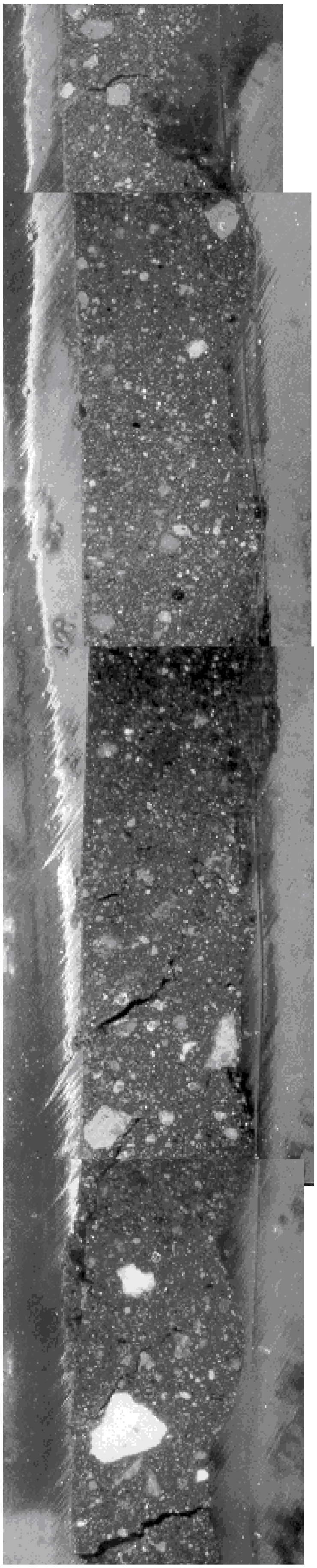
bottom,
maybe

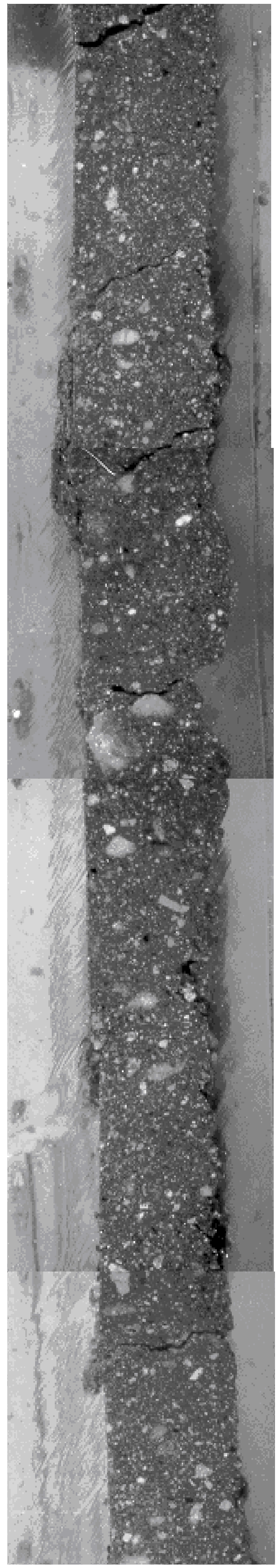
top

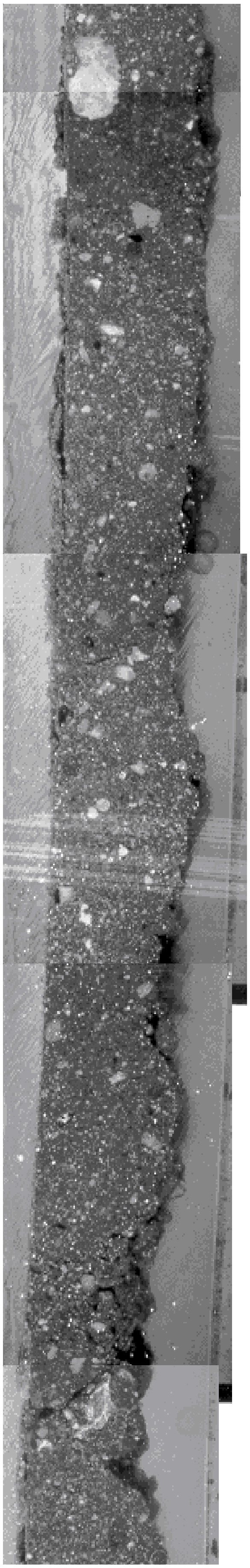
about 141 cm

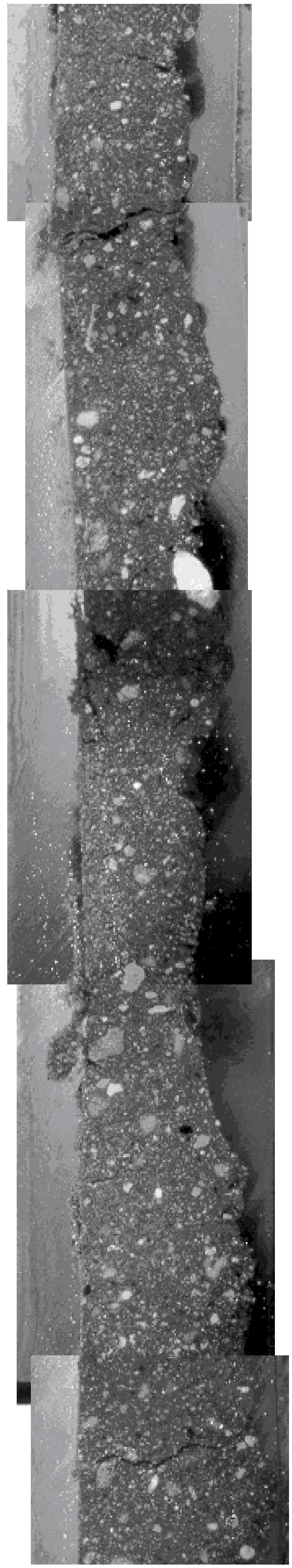


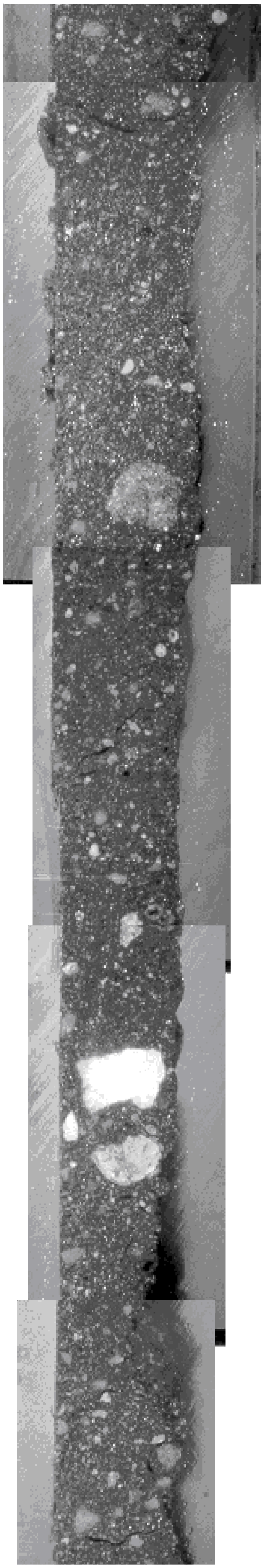
60003,

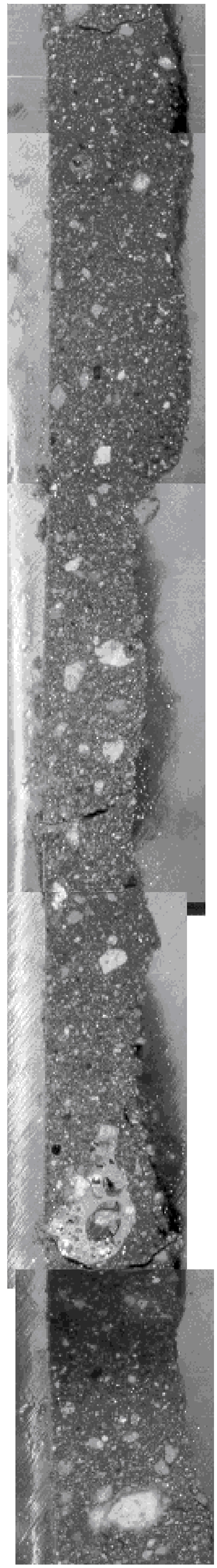


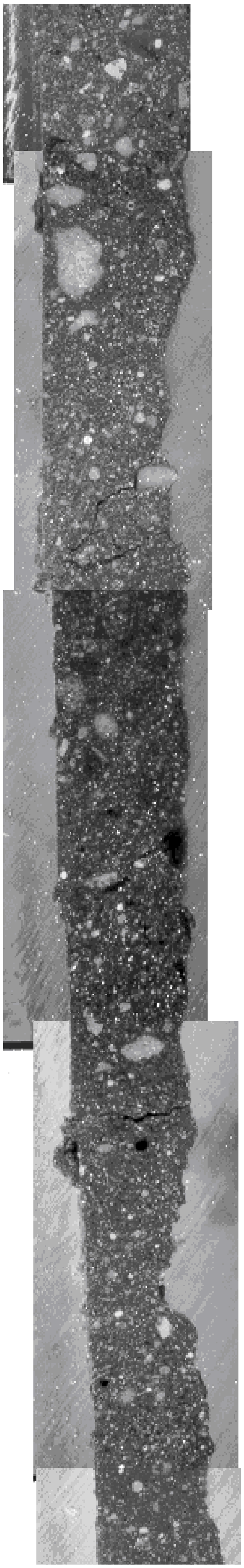


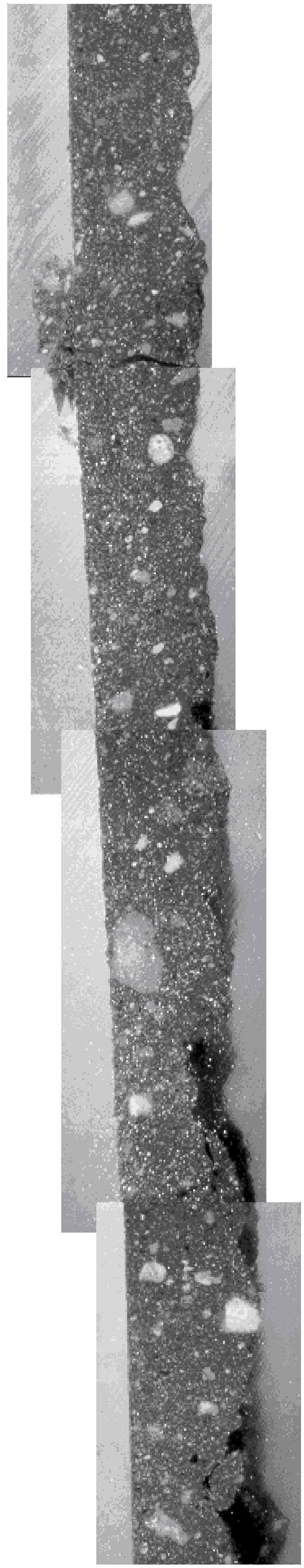


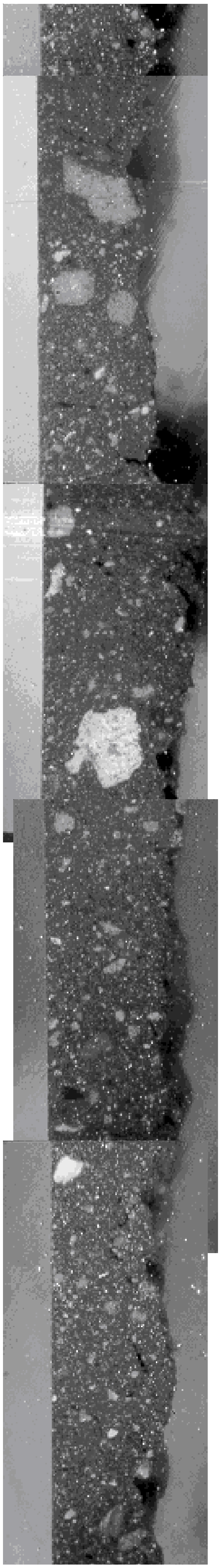


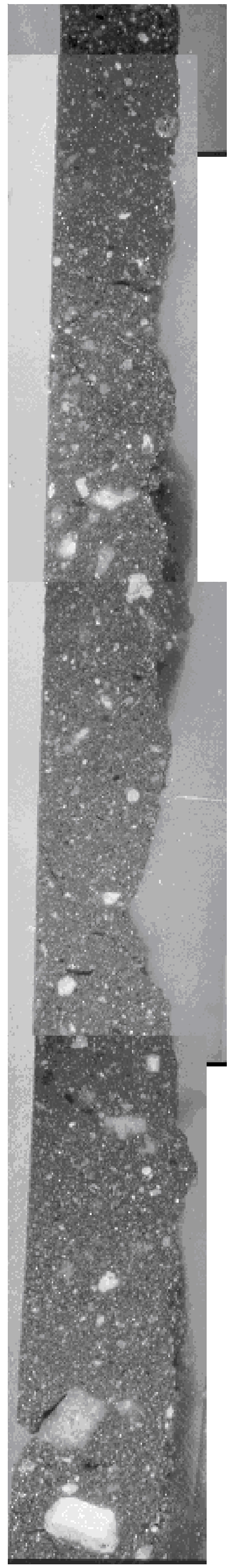


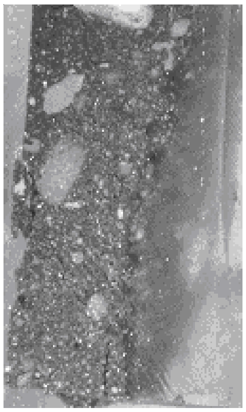






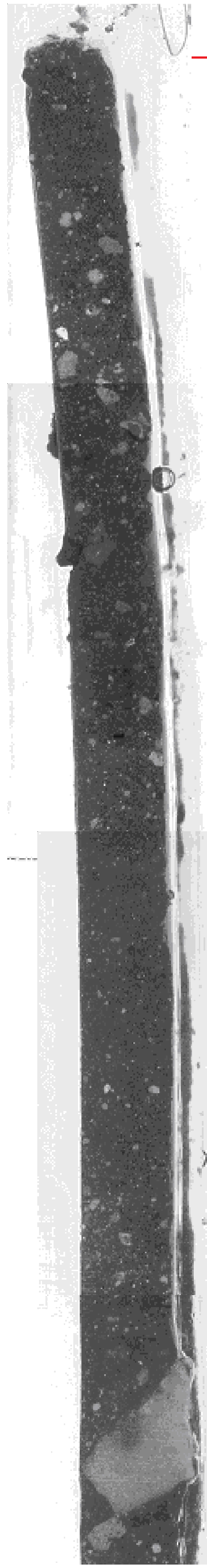






about 180 cm

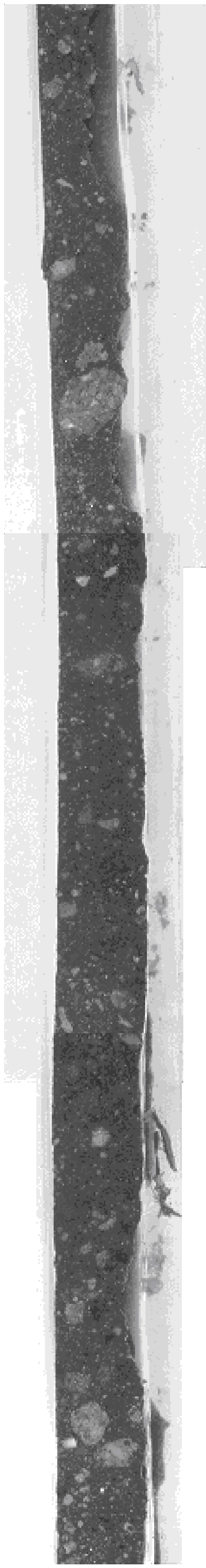
bottom of 60003

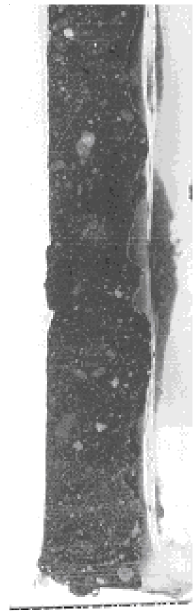


about 181 cm

top of 60002

at about 190 cm there
is buried treasure





about 216 cm

bottom of 60002

60001 (bit)

additional 5.5 cm

60001-7 References

(note: There is a vast literature on the lunar drill cores, which can not all be listed at once. Please excuse the complier for his brevity.)

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